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STABILIZATION AND CONTROL OF LOCAL ROCK FALLS AND DEGRADING ROCK SLOPES

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SUMMARY

The paper describes design and construction techniques for the stabilization and control of local rockfalls and the products of general degradation from rock slopes. Stabilization measures are discussed and illustrated by a series of idealized cross-sections and examples. Simple nomograms are developed for the design of rockbolt installations and rock-trap ditches.

Introduction

Background

The intention of this paper is to discuss design and construction techniques for natural and artificial rock slopes where only minor or local instability is likely to occur or where the slope is liable to slow degradation due to natural weathering. The need for local remedial work on rock slopes, especially where the differential weathering of relatively hard and soft beds is involved, has long been recognized. Many of the basic techniques were developed in Britain at the time of Brunel and Stephenson as can be seen in major rail cuts excavated in the early and middle parts of last century.

With the development in the last two decades of efficient rock bolting systems and of the ability to predict large slope failure with considerably more certainty than hitherto (Hoek & Bray 1974) it is timely to consider separately the stabilization and control of smaller local rock falls and degrading rock slopes.

Natural geological features are labelled in Fig. 1 in the terms used in this paper and the diagram gives an impression of the scale of 'local' rock features. In general rock failure mechanisms are independent of scale, but the means for their prevention and control are discussed here in the context of either a small failure, involving up to tens of tons at any one time, or piece-meal failure by degradation. Weathering plays a most important part in conditioning the slope to fail.

Design considerations for small scale instability

Site investigation and assembly of data

The object of an investigation is to collect information to enable design for the control of minor rockfall and slope degradation to be made on a rational basis. The principal geological information required is a picture of the geometry of the slope, the properties of the intact rock, the nature and geometry of the discontinuities, the groundwater conditions and the weatherability of the rock.

Small-scale instability of all types develops from localized and probably less predictable vagaries of structure compared with major falls, and from blast fractures and overbreak. The most important stage in design therefore is the close inspection and mapping of each fresh exposure. Even with the most thorough investigation and documentation, detailed form of near surface discontinuities, the local influence of water and *in situ* stresses and the long-term effects of weathering are largely a matter of experience and judgement and must be accommodated by conservatism in design.

Stabilizing measures against small failures and slope degradation

The measures used to stabilize potential small failures and general degradation are discussed in the order in which the work would probably be carried out, and are illustrated by a series of cross-sections (Figs. 2, 3, 8 and 9). Appropriate techniques for a particular site may only be selected after consideration of the geometrical and economic constraints and safety requirements. In a complex situation basic design decisions may only be made as the face is exposed.

Prior to Excavation. Before work on the slope commences it may be necessary to shield or strengthen structures against blast damage, and to erect temporary or permanent protection from rock fall at the toe. The face should be kept free from continuous water flow, and, if the final profile is known, the installation of ditches and the permanent diversion of existing water-courses at the head of the slope should be arranged. Outline mapping of all geotechnical features relevant to the design should be carried out at this stage, together with other site investigation work.

During Bulk Excavation. If major instability is unlikely, the choice of slope angle is based on engineering judgement and experience. Such experience has been embodied in the recommendations of the British Standard Code of Practice on Earthworks, CP 2003 (1959), Table 3 'Design of slopes in Rock Formation', where slope angles from 45° to 90° are recommended, depending mainly on rock type.

Each slope must be treated individually but local practice may be a guide. The flatter the slope, the greater are the excavation costs but the long-term maintenance costs are less. The principal design decision is often whether to form the slope in a series of benched steps or to cut to a uniform gradient. A slope trimmed to the inclination of massive beds will be relatively maintenance-free. Alternatively a bench (Fig. 2) may be used as an access road, a rockfall arrester and as the basis of a contour drainage system. To allow for machine access in the clearing of the benches of major slope cuts, bench widths should not be less than 5 m. For access to scale the rock slopes, bench heights would not be greater than say 12 m. Slope contours may be modelled to reduce snow drifts and the impact of gusting winds. The influence of the geology should be understood before the design decision is reached.

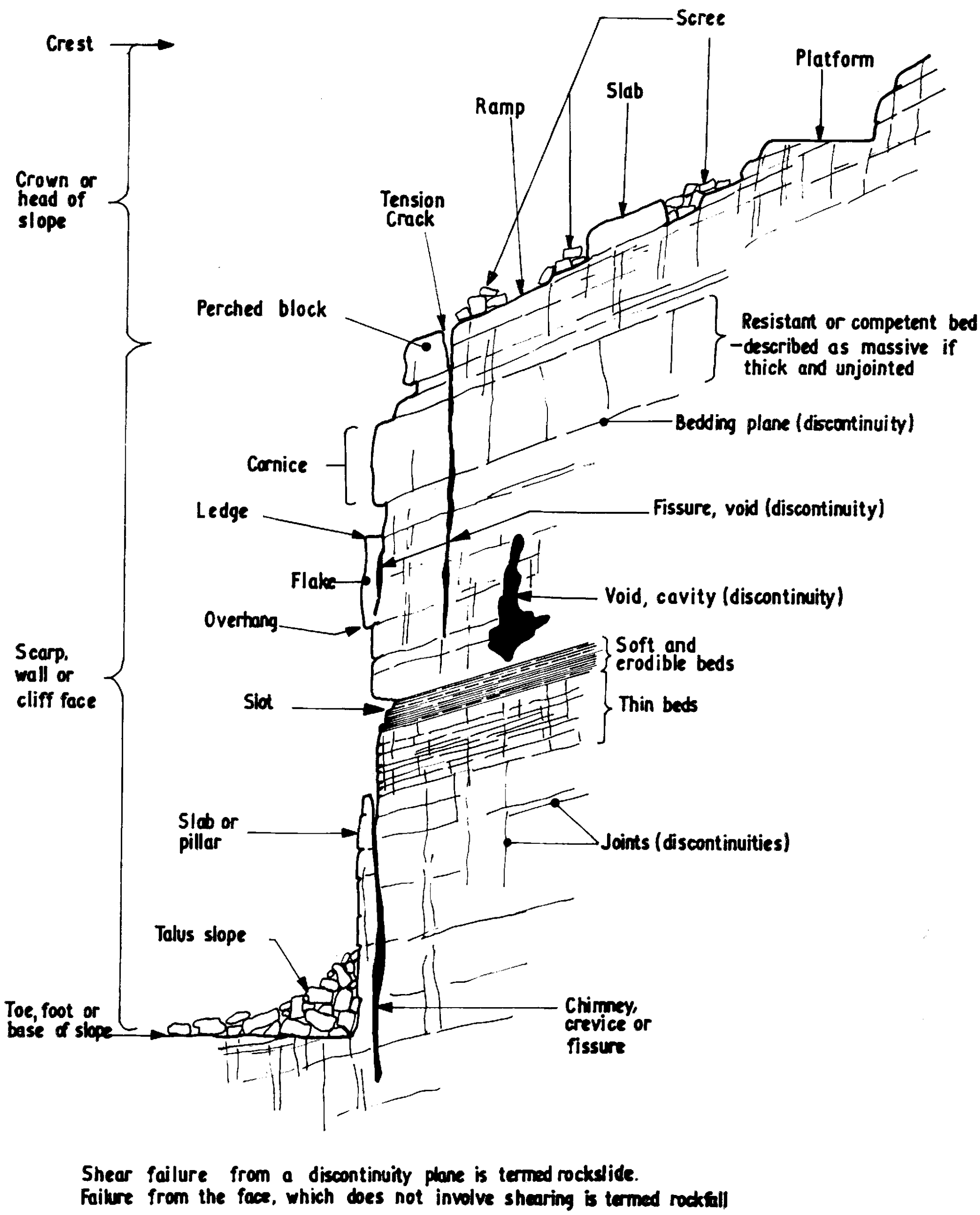

FIG. 1. Simple descriptive terms for rock slopes.

A cutting will generally be opened by trial blasts and the opportunity should be taken to investigate the variation in overbreak and fracturing with blasting technique. Close trimming of faces by pre-split blasting (Langefors & Kihlstrom 1963) may permit the use of steeper slopes. As excavation proceeds, the geological structure should be mapped in detail, at whatever scale is appropriate to the potential instability, and a schedule of stabilization measures drawn up (e.g. Fig. 15 of Dearman & Fookes 1974). As a general rule if structural restraint is required it should be applied to the slope face as soon as possible after excavation, before the strength available in the first stages of joint dilation is lost during slope heave. If the cutting is taken down in level stages, then mapping and stabilization treatment should closely follow excavation at each level.

On an existing slope, bulk excavation may consist simply of removal of individual blocks of rock, in such a condition where stabilization would be more expensive than disposal. Access is often difficult and the method of excavation depends on the proximity of engineering and other structures at the toe. Removal may be achieved by controlled blasting, or, if toe conditions do not permit this, piecemeal breaking *in situ*. On a recent site with restricted access at the toe, overhanging blocks were lifted clear of structures by crane from above using slings or hooks anchored by resin into individual blocks.

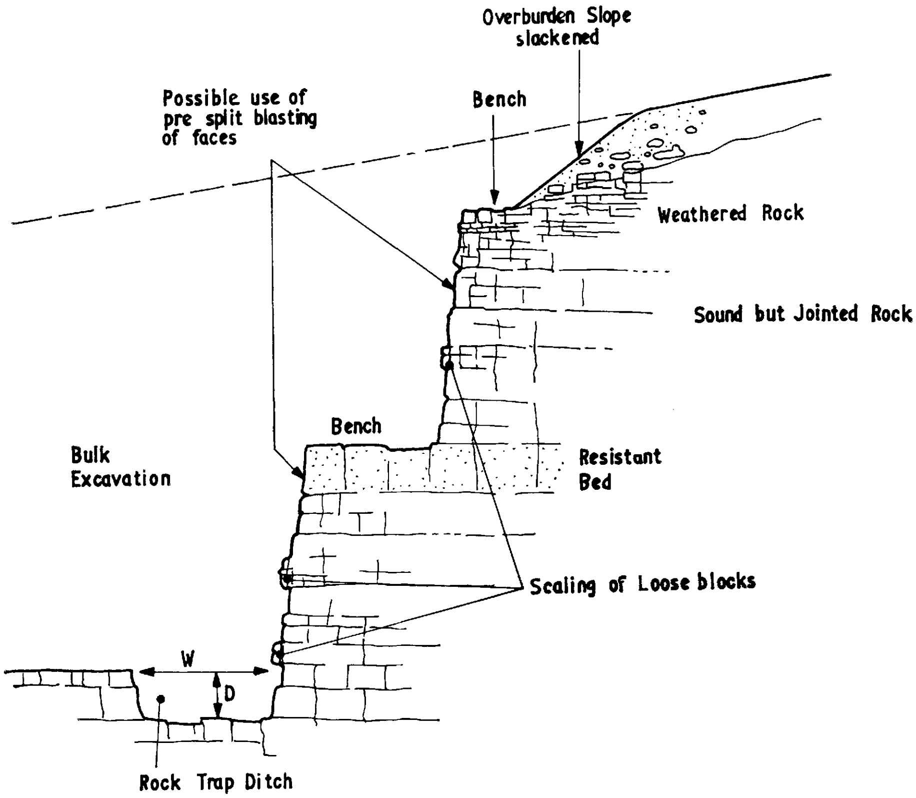

FIG. 2. Face treatment immediately following bulk excavation.

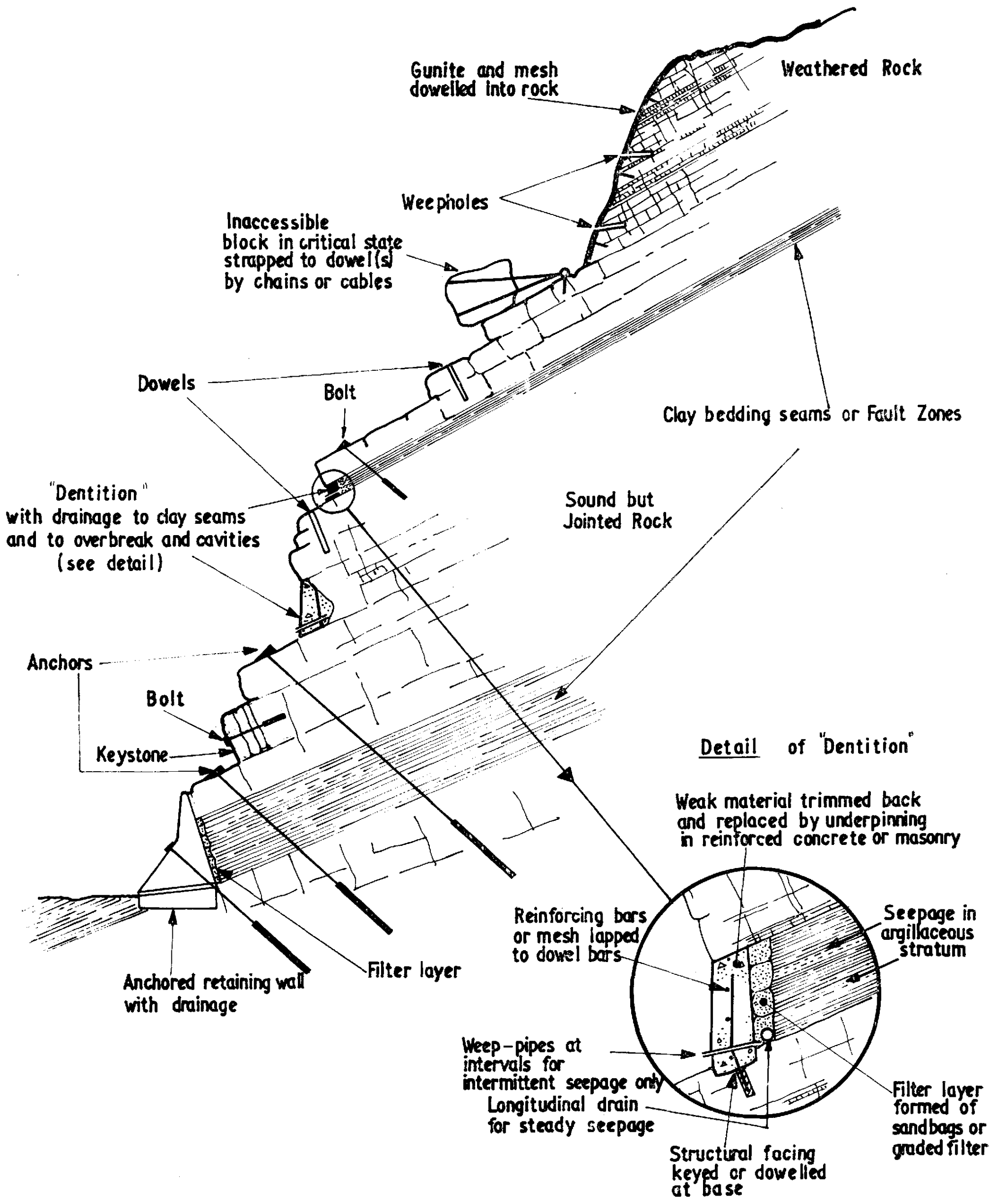

FIG. 3. Minimization of rockfall by structural means.

Detailed structural work on the rock face

Rock face support methods

A concrete or masonry wall may be necessary to sustain the load of a major rockslide, and is most efficiently used in conjunction with rock anchors (Fig. 3). The structural design of such a system is beyond the scope of this paper but is discussed for example in Pacher, 1957. Less rigid, and possibly more economic buttressing systems include crib walling, soil or rockfill berms and structures built from stone-filled gabion baskets.

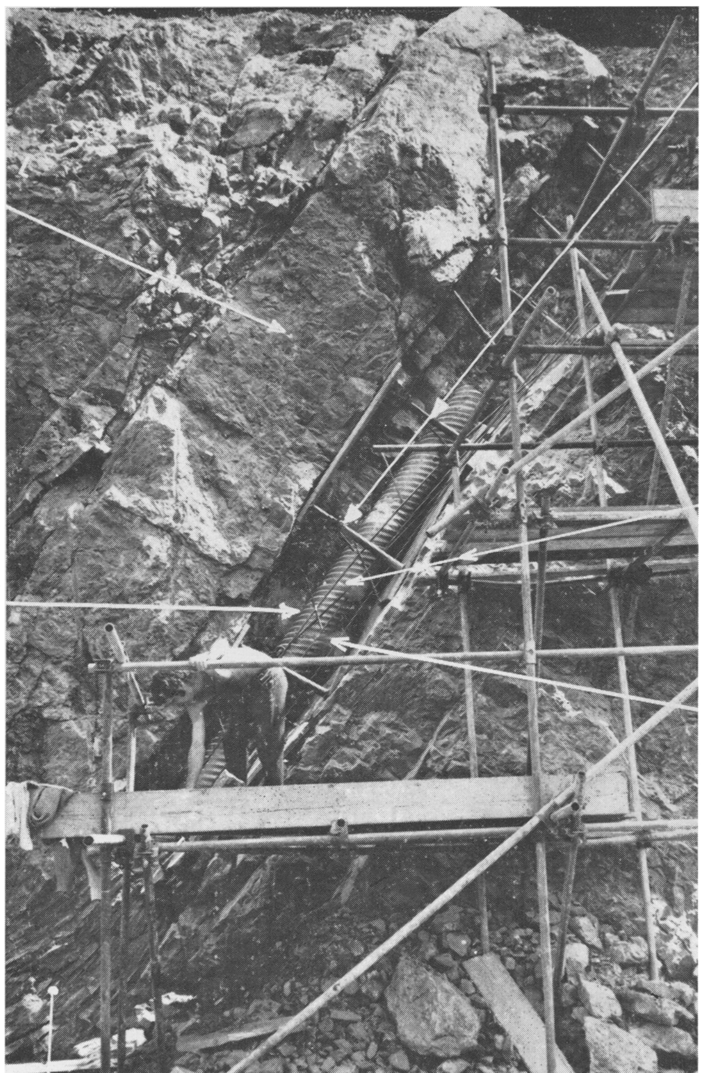

FIG. 4. Construction of dentition facing to soft layer.

Wherever the face is covered by an impermeable buttress there is the possibility of groundwater accumulation in the rock mass. Pore pressure build-up and frost action promote instability and it is good practice to incorporate a drainage layer between the rock and the facing. If, with long term seepage, there is a migration of fines, and a possibility of either clogging the system or undermining the slope, the free-draining layer should be designed according to the established filter rules on grain size (Cedergren 1967). Special drainage provision should be made at the emergence of springs (Figs. 3 & 8).

For local stability problems *ad hoc* support systems are applied to suit the geology and geometry of the face. Much use can be made of mass and reinforced concrete and masonry in the form of structural 'dentition' (Fig. 4) to prop individual blocks of rock liable to roll, topple or disintegrate and to underpin overbreak cavities and overhangs. In dental work built up from the toe of the slope, bands of soft material are trimmed back and the resulting slots packed with stockings or bags filled with a suitable filter material and faced with rough masonry or reinforced concrete. Weep holes should be introduced at frequent intervals. All cavities and fissures which could promote rockfall would be similarly treated. The completed dentition may be in the form of regular bands bridging between competent beds, or an irregular patchwork tracing faults, bedding and overbreak. The work may be self supporting in chimneys or may be dowelled into the solid rock. This type of treatment must be tailored with an eye to detail, and labour costs are inevitably the largest item on the bill. Masonry work in stone taken from the face often weathers less obtrusively than concrete.

Nominal structural facing should be provided for self-supporting areas where rapid, progressive weathering may occur. Typically the exposures of fault zones, and the incompetent mudstones of a coal measures sequence for example may be eroded leaving dangerous overhangs. If large areas are to be treated, the use of sprayed gunite may be economic. Detailed face preparation is required for guniting; reinforcing mesh must be dowelled into the rock and formed to accommodate irregularities in the face. The reinforcement would typically be an electrically welded mesh 100 mm square and No. 9 s.w.g.; for heavier restraint the mesh could be supported rockbolts. Guniting techniques have recently been reviewed by Ryan (1973). Alternatively, and more simply, small areas may be protected by mortar screeding. Where the facing is necessarily applied directly to rock, drainage should be assisted by weepholes. Weathering protection to a gentler slope may be provided by gabion-type mattresses or, where groundwater erosion is not anticipated, by vegetation cover.

During recent work on an existing slope, excavation revealed unexpected difficulties and the stability of overhanging blocks became critical as it was felt that drilling operations would be likely to trigger a fall. Individual blocks were therefore strapped by chain and cable either to massive rock outcrops or to dowels set back in the face, and either bolted, broken *in situ* or hauled up to stable positions. Blocks would only be strapped permanently on a hillslope inaccessible to plant, where the operation could be caried out manually by a maintenance gang.

Rock reinforcement methods

The simplest of these methods is the use of steel *dowel bars* as shear keys, typically to knit together medium to thinly bedded material dipping parallel to the slope. Holes would be drilled normal to the bedding and the bars grouted in with any potential shear surface at mid depth. Dowels are unstressed and weak in bending and therefore would only be used where the discontinuities are narrow. A dowel bar would be 15 to 30 mm diameter and 1 to 2 m long.

Reinforcement is used more efficiently when the steel is in tension, when compression induced in the rock mass improves shearing resistance on potential failure planes. A *rock bolt* is anchored to the inside end of a drill hole across a shear plane and tensioned from the face. Rock bolts are used in slope stabilization either individually in the restraint of rock blocks and wedges or in close-centred arrays to provide support to large areas or in complex structural situations. Typically a bolt would be 25 to 40 mm diameter, $1\frac{1}{4}$ to 8 m long, with a tensile working load of up to 100 kN. Longer and more highly stressed bolts are also used. Rock bolting techniques have been described at length by Lang (1961), Murphy, Whittaker & Blades (1972) and Littlejohn & Bruce (1975). The basic elements of the system comprise the drillhole, the anchor, the bolt and the bolthead fixing at the face. If drilling is difficult, or if soft zones are encountered in the drillholes, it may be necessary to reduce hole size with depth and to support the hole with a liner tube. A variety of anchoring techniques have been developed in the mining industry, but the advantages of resin bonding for this type of work have become apparent. The speed and ease of installation, the cheapness, flexibility and reliability of the methods have been brought out in case histories by Askey (1971), Edwards (1971) and Eyre (1973). The bolt would generally be a single deformed mild steel bar, but where access is restricted short lengths could be coupled together. Effective grouting is difficult with large diameter couplings. Using a torque spanner, the nut at the bolt-head should be tightened on to a faceplate of sufficient size to spread the load. The plate should be located or protected so that the bolt will be unaffected by weathering and would normally be set square to the bolt on an *in situ* mortar plinth. Rolled thread is preferable to cut thread to resist the torsion induced in tightening the bolt. The steel between anchor zone and faceplate should be protected from corrosion by surface treatment or grouting. It should be ensured that grouting pressures do not promote instability. In a novel or large scale installation the use of the system should be verified by pullout tests (Franklin & Woodfield 1971), and long term monitoring of bolt loads (Roberts 1966).

Given the uncertainties involved in the prediction of small-scale instability it will rarely be possible to detail bolt loads to a known safety factor. Some insight into the problem is afforded however by setting up simple mechanical models of the sliding and toppling of a block resisted by rock bolting. Consider for example the instability of a block of weight W, resting on a plane dipping at an angle θ, with pure friction between block and plane. From simple statical calculations, the bolt load T required to prevent sliding is plotted as a fraction of the weight of the block, against variables ϕ and θ for the case of a bolt installed normal to the plane (Fig. 5); in Fig. 6 the bolt is inclined at the friction angle ϕ to the plane. The advantage of inclining the bolt is clear.

The potential error in the practical application of such a model lies in the neglect of cleft-water pressures and in the estimation of ϕ. For example, the load on a horizontal bolt through a block of dimension 1 m $\times$ 1 m $\times$ 1 m, with W $=$ 3000 kg/m^3, on a vertical face ($\theta = 90°$), ignoring water and assuming $\phi = 35°$, from Fig. 5 is T $=$ 1.45 W, or T $=$ 43 kN. With hydrostatic water pressure in the cleft, the bolt load T $=$ 47 kN, i.e.

an increase of 10%; for $\phi = 25°$, plus water pressure, T = 68 kN, an increase of 60%. For practical use a generously judged safety factor should be applied to the chart value. The benefit to be gained from slope drainage is apparent.

It is often necessary to bolt a block undermined by weathering and balanced on a precariously narrow ledge. The passive load that the bolt must sustain to prevent toppling from a ledge on an overhanging face is tabulated in Fig. 7, for bolting normal to the face. Similar reservations apply here concerning the influence of water pressures. Edwards (1971, para. 7i) indicates that values of $T/W = 0.5$ (for sliding) and $T/W = 1$ (for toppling) were used in the Lune Gorge rock bolting installation.

Such crude models of bolt function as have been outlined above provide a basis for a more rational approach to design. Short tensioned bolts, bonded along their full length, are intermediate in action between the dowel and the bolt. However, the limits of application for this type of unit have yet to be investigated in field trials.

Rock anchors are used for major stabilization work of all types, particularly in conjunction with retaining structures. The use of multi-tendon cables, stressing and grouting

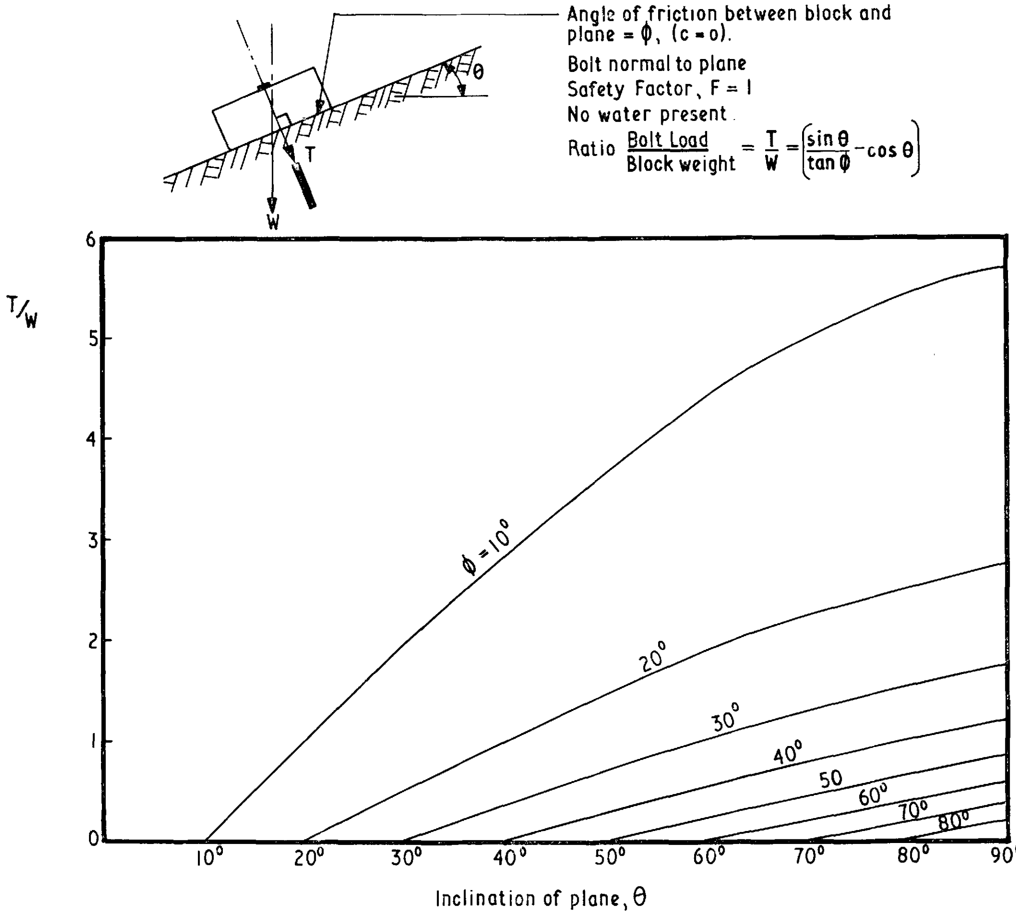

FIG. 5. Rockbolt tension required to prevent block of rock sliding down inclined plane.

techniques has been developed especially in the field of dam construction using techniques originating from pre-stressed concrete work. Anchors have been loaded from 100 to 5000 kN and lengths greater than 30 m have been used. Stress levels are far greater than those involved in rock bolting work, so that anchor loads are dependent to a greater extent on rock type and rock structure. The design of rock anchor systems is beyond the scope of this paper but has been dealt with by Littlejohn (1970) and Hoek & Bray (1974).

Detailed drainage work on the rock face

On a cut slope in Britain, small scale instability is in general mainly promoted by the wedge action of frost, ice and cleft water in near-surface discontinuities. The effect of free water on the stability of a bolted block has already been indicated. To establish stable conditions it is therefore essential and economical to use some form of slope drainage (Fig. 8). Firstly, measures must be taken to prevent the infiltration of surface water in the vicinity of the slope. The most commonly used form of drainage is a ditch at the head of the slope. The ditch may re-channel an existing permanent flow or may simply collect upslope runoff. The construction of an impermeable lining reduces maintenance and minimizes infiltration.

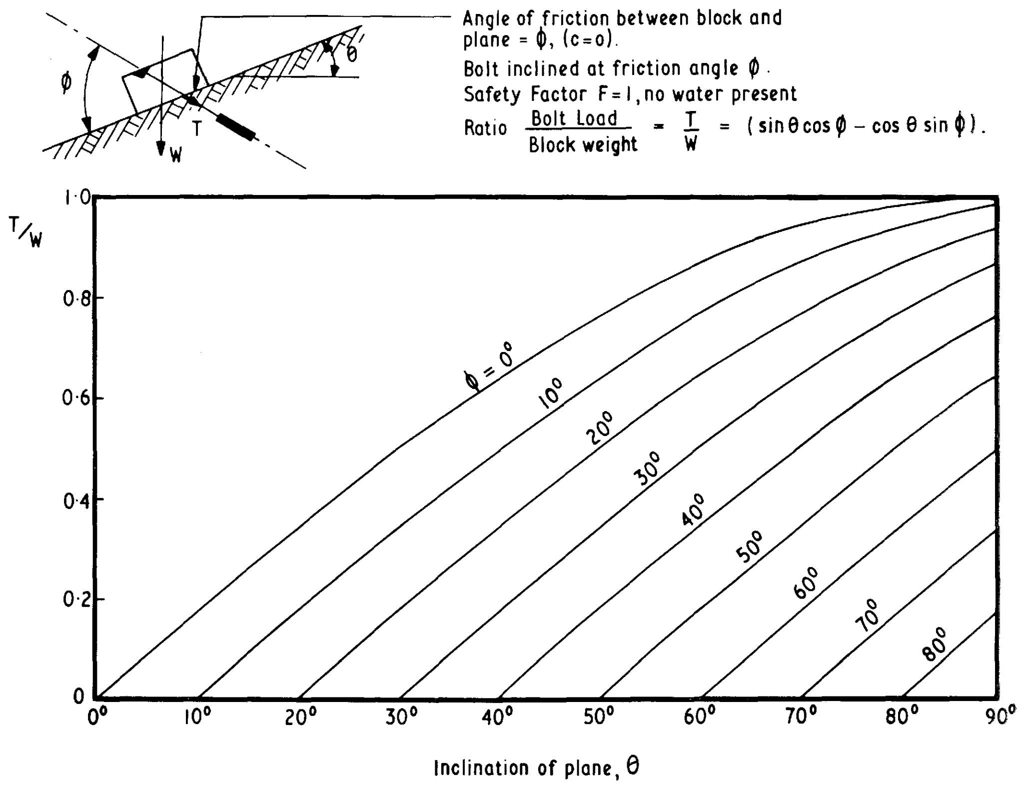

FIG. 6. Rockbolt tension required to prevent block of rock sliding down inclined plane.

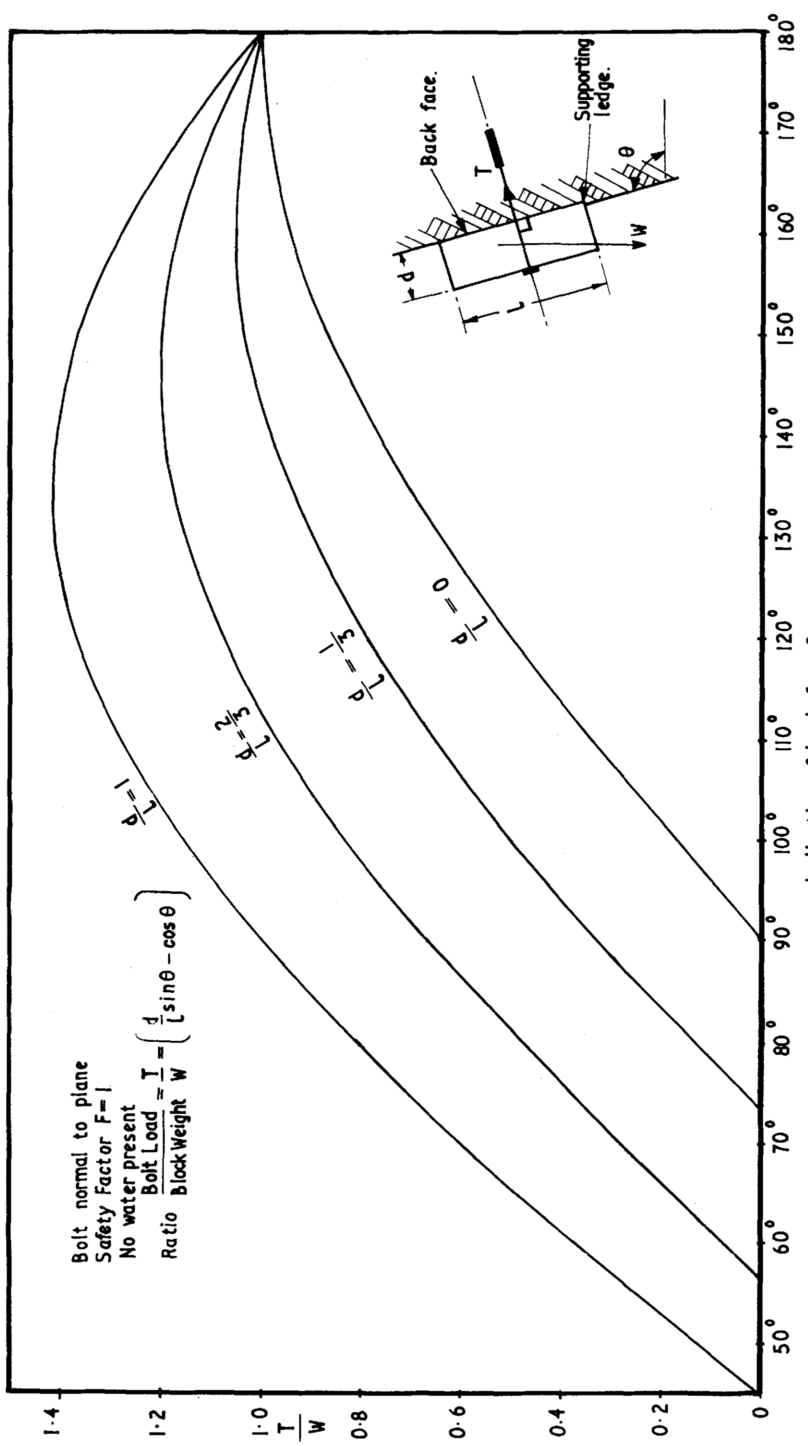

FIG. 7. Tension to be sustained by rockbolt to prevent block toppling from ledge.

Ditches should be located so as to avoid both existing and potential instability as should all downpipes and flumes leading to the toe of the slope. Midslope drainage ditches may be installed on benches but it is important that they should be kept free of debris. General infiltration of surface water into the rock jointing system may be minimized by sealing major tension cracks with pointing or cement grout and by screeding irregular horizontal surfaces. All paved or screeded surfaces should be formed to direct water into surface drainage channels.

Secondly, and often of greater importance, all groundwater should be controlled at or before emergence at the surface. Piezometry, permeability testing and flow net construction can rarely be used to predict the effect of jointing anisotropy and stress release, and the existence of faults and low permeability horizons, at the small scale with which this paper is concerned. Springs and seepages are often concentrated at the outcrop of less permeable and more erodible material. To prevent undermining, drainage of the slope

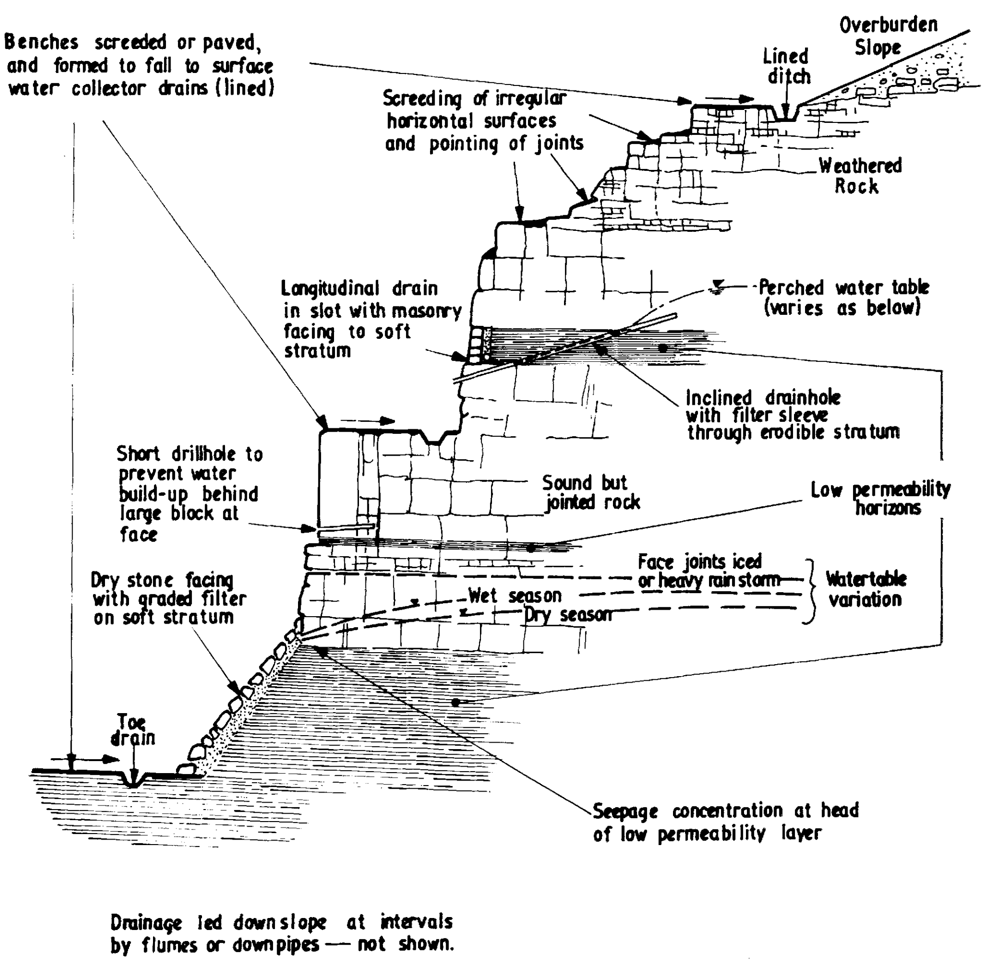

FIG. 8. Minimization of rockfall by drainage measures.

face would generally be undertaken in conjunction with dental masonry or concrete as discussed previously, or by the use of a permeable revetment such as dry stone walling seated on a granular filter bed. It may be necessary to tap groundwater some distance in from the face by means of raking drainholes or drainage adits but such expensive measures would usually only be considered in dealing with large-scale instability. The cheapest way to reduce water build-up behind individual blocks is by drilling short drainholes at close centres to penetrate water-bearing fissures.

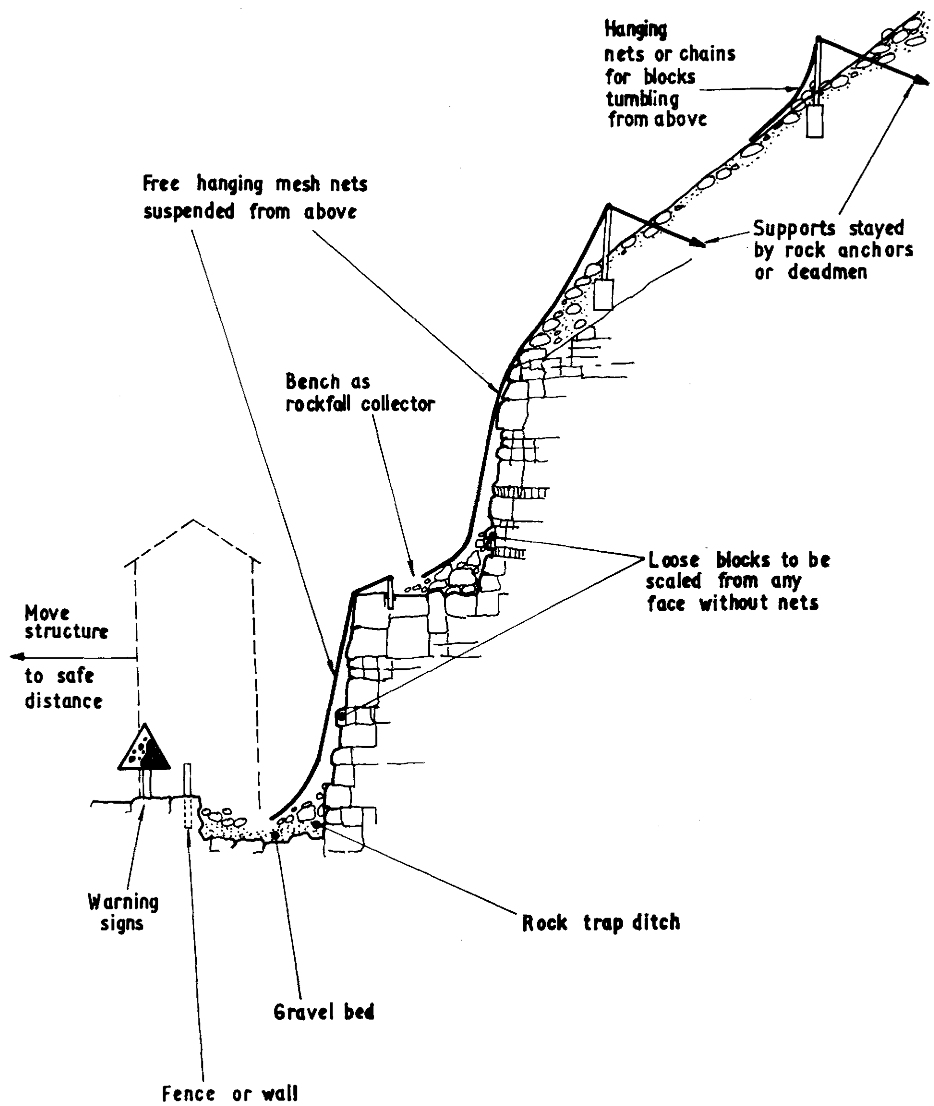

FIG. 9. Rockfall control measures.

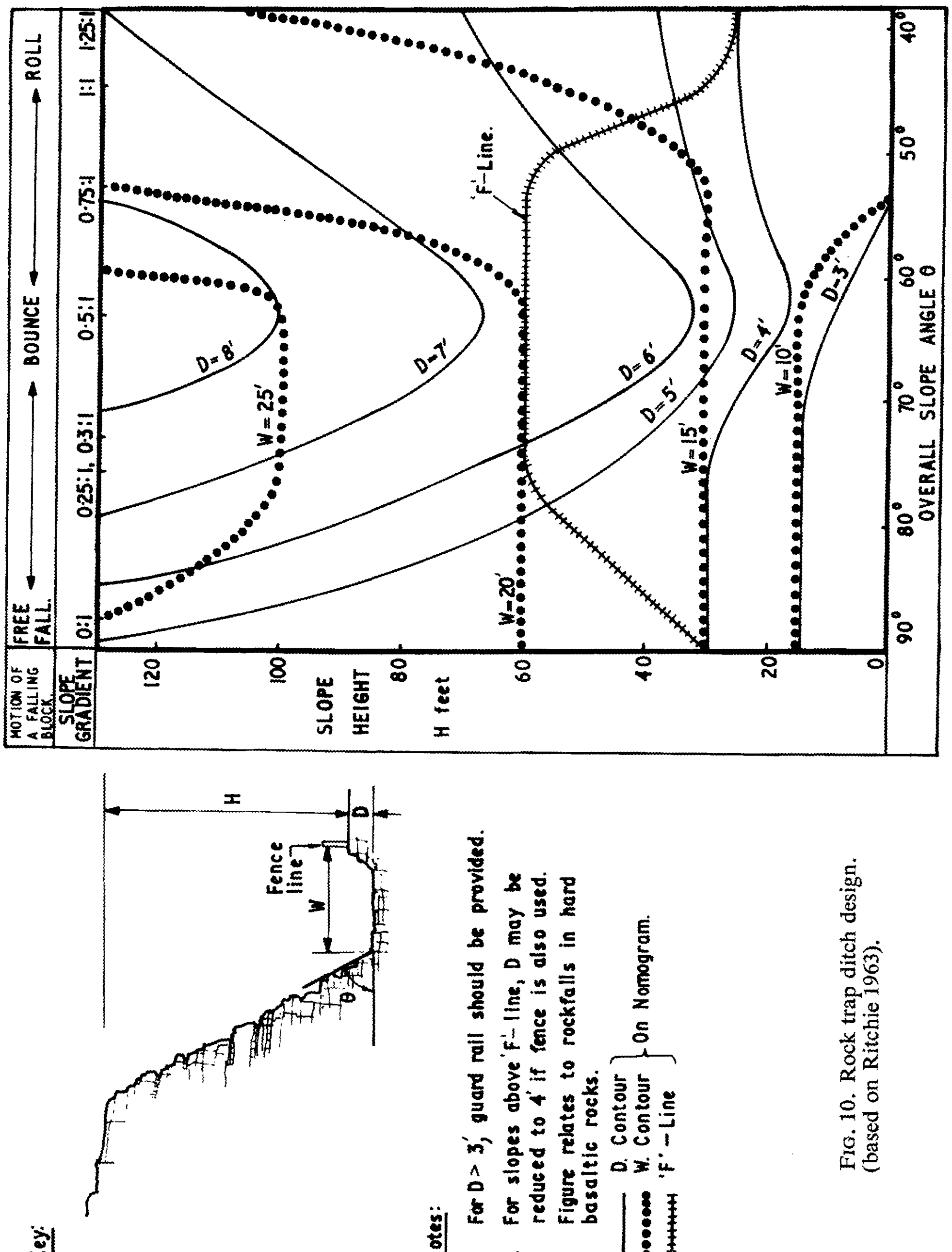

FIG. 10. Rock trap ditch design.
(based on Ritchie 1963).

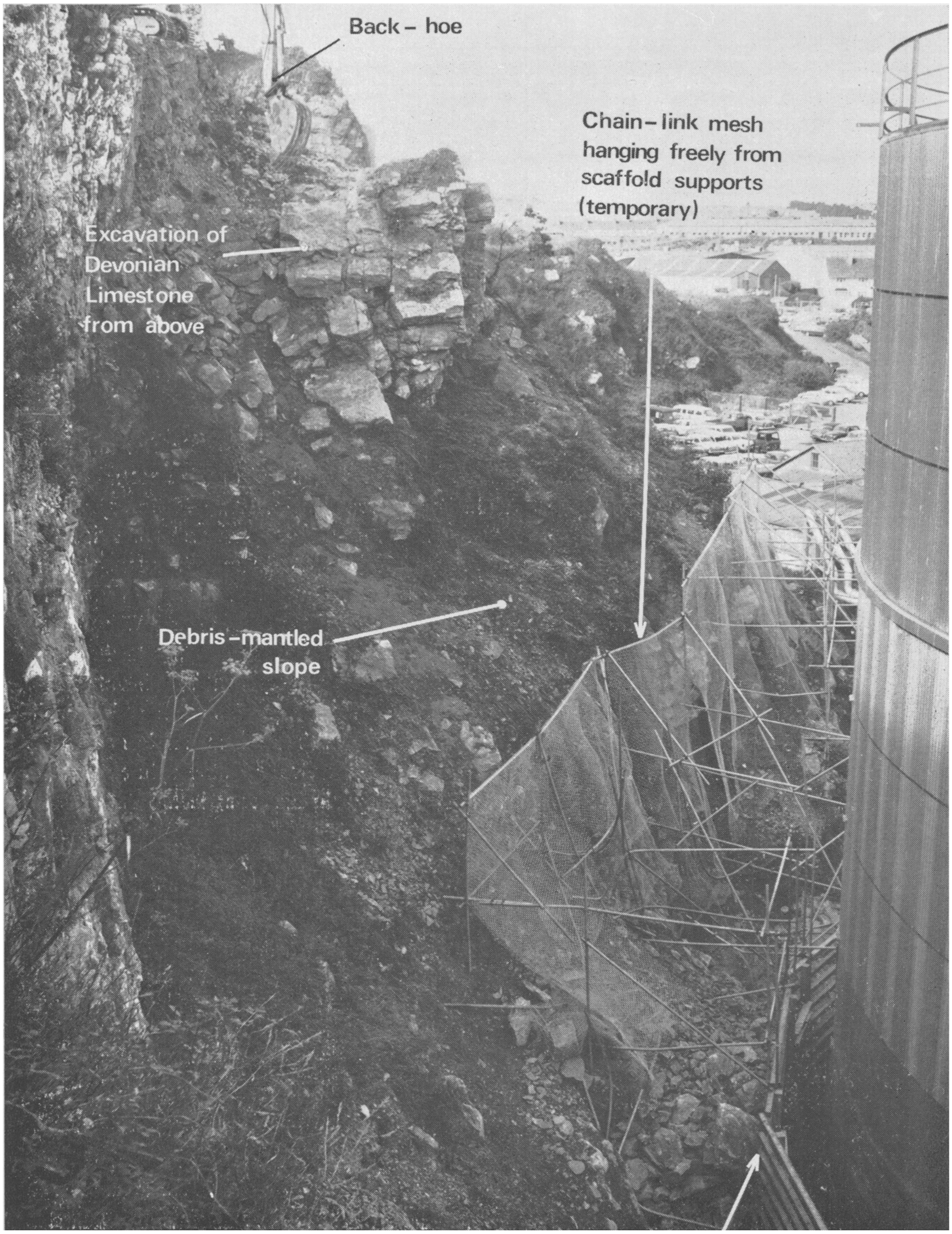

FIG. 11. Rockfall protection during construction by temporary scaffold and mesh.

Rigid fence anchored to rockhead (permanent)

STABILISATION MEASURES

FAILURE TYPE		EXCAVATION: FLATTEN SLOPE	EXCAVATION: BENCH	EXCAVATION: LOCAL EXCAVATION	STRUCTURAL SUPPORT: GUNITE FACING	STRUCTURAL SUPPORT: PERMEABLE (MASONRY) FACING	STRUCTURAL SUPPORT: LOCAL STRUCTURAL "DENTITION"	STRUCTURAL SUPPORT: BUTTRESS	STRUCTURAL SUPPORT: ANCHORED WALL	STRUCTURAL SUPPORT: STRAP	STRUCTURAL SUPPORT: DOWEL	STRUCTURAL SUPPORT: BOLT	STRUCTURAL SUPPORT: ANCHOR	DRAINAGE: DRAINAGE DITCH	DRAINAGE: SCREEDED (PAVED) SURFACE	DRAINAGE: SHORT DRAINHOLES	DRAINAGE: LONG DRAINHOLES / ADITS	ROCKFALL CONTROL: MOVE STRUCTURE / HIGHWAY	ROCKFALL CONTROL: ROCK TRAP DITCH	ROCKFALL CONTROL: ROCK TRAP FENCE / WALL	ROCKFALL CONTROL: NETTING	ROCKFALL CONTROL: SCALING OF LOOSE BLOCKS
PLANE FAILURE	LARGE	1	2	3	3	3	3	1	1	2	3	1	1	1	1	1	2	2	2	2	3	2
	SMALL	2	2	2	2	3	2	1	1	2	3	1	2	1	1	1	3	2	1	1	1	1
WEDGE FAILURE	LARGE	1	3	3	3	3	3	1	1	3	2	2	1	1	1	3	1	2	3	3	3	3
	SMALL	1	2	2	3	3	2	1	1	1	1	1	3	1	1	2	2	2	2	2	2	2
TOPPLING	LARGE	1	3	3	3	3	3	2	2	3	3	2	1	1	1	3	1	2	3	3	3	3
	SMALL	2	2	2	3	3	2	2	3	2	2	1	2	1	1	2	2	2	2	2	2	2
ROCK OR DEBRIS FALL & GENERAL DEGRADATION	LARGE	1	2	2	2	2	2	1	1	2	3	2	3	1	1	1	3	2	2	2	2	1
	SMALL	2	1	1	1	1	1	1	1	2	2	1	3	1	1	1	3	2	1	1	1	1

1.— Use will be beneficial.
2.— Possible use depending on situation.
3.— Use unlikely to be economic or effective.

TABLE 1: *Rock slope failure types and some appropriate stabilization measures.*

Rockfall control

On a site examined recently, the most economical way to protect an industrial structure from rockfall was to move the structure to a safe distance. There is no such opportunity to protect, say, a highway in a cutting, and it may be cheaper to permit rockfall, which can be controlled in a variety of ways (Fig. 9), than to stabilize the face.

If a structure is a small distance from the toe of an unstable slope a rock trap can be built by strengthening the walls or by construction of a separate fence. But for a structure at the toe of the slope it may be necessary to build a rigid awning out from the face, as is used on coastal roads and railways below disintegrating sea cliffs. Ritchie (1963) provides a useful guide to the dimensions of a rock trap or ditch from his experiments on a variety of existing slopes, generally in hard basaltic rocks, using an adjustable towed trailer to simulate a ditch cross section. His results were presented in the form of a table of ditch widths (W) and depths (D) necessary for a range of slope angles and heights. For easier application this tabulated data has been plotted in Fig. 10 from which values of D and W may be taken directly for any given slope height and angle. These values can be reduced if the base of the ditch is covered with an earth or gravel layer, if the face is netted, if a fence is used (as indicated on the figure), or if the slope is cut in soft rocks. The rocktrap should be accessible for clearing. The degree of additional structural support necessary on the face depends on the volume of potential rockfall. On a site recently visited by the authors a ditch adequate to contain minor rockfall had been filled by a collapse of one large overhanging block. The broken block had formed into a chute and the fall of overlying debris was directed towards a vulnerable structure.

Rockfall warning signs should be erected on the approaches to an area exposed to rockfall. Automatic alarm systems have been developed and fitted to protective fences (Eckel 1958, Fig. 97). Rockfall at the toe will be reduced by the use of midslope benches; however, flat, unfenced benches should not be used in conjunction with graded slopes as rolling blocks would be projected from them.

Most falling rock may be kept close to the face by a free hanging mesh net suspended from the top of the face. If the rockfall is of sufficient magnitude, a single chain-link mesh would unravel over the width of a panel, whereas a heavier twisted wire mesh may be broken locally but would still serve its purpose. On a slacker slope or on scree, the energy of rolling and bouncing boulders may be much reduced by trailing wire nets or even chains suspended some few feet above ground level (Figs 9 and 11).

Post Construction

Ideally the installation of stabilization measures should be recorded on 'as-made' drawings based on the original slope maps and photographs, noting such detail as gunite thicknesses, mesh sizes, rock bolt and drainage specifications.

The slope should be inspected at intervals by an engineering geologist or rock engineer to check that the original drainage and structural works are functioning, and that weathering has not led to dangerous undermining. If a periodic photographic record is maintained, the deterioration of the face can be best assessed by photographic comparison. Instrumentation records should be updated and the instrumentation should be extended and renewed where necessary. The inspection is simplified if the locations of bolts, dowels, concealed drainage runs, property boundaries and 'key' blocks are picked out on the face in a 'day-glo' type paint.

For slopes with a safety requirement but minimal rock trap space, the periodic scaling of loose blocks is the usual form of maintenance. Access for scaling may be by scaffold, tower crane, or from an inspection cradle. The scaling operation may be confined to small blocks which can be manhandled and lifted out from above or much larger blocks which can be barred from the face and disposed downslope. Vigorous attempts to dislodge the stable blocks may well be harmful to long-term stability and undercutting must be avoided.

Conclusions

Local rockfalls and degradation of rock slopes depends on the interrelation of rate of weathering and erosion, local rock type and structure, local climate and groundwater conditions. A thorough investigation of these conditions requires mapping and other observations on the local structure and general rock conditions, a range of tests for rock durability and strength, and local characteristics of failure mechanisms.

Individual methods for stabilization will rarely be used in isolation. An efficient design will generally involve a combination of drainage, structural restraint and passive control. The principal stabilization measures appropriate to different failure types are summarized in Table 1.

Field trials are sometimes conducted to investigate specific aspects of the work such as excavation techniques, ultimate loads on anchors, and the effectiveness of rock trap ditches, but the long term monitoring of the degradation of cut slopes is rarely attempted. Research is needed into the weatherability of rock faces and engineering knowledge and judgement would be greatly enhanced by the publication of regional studies and case histories on this topic.

Small scale stabilization work is often necessarily conducted in a piecemeal and exploratory manner. Accurate billing and measurement of the operations is impractical and thus much of the work may be carried out on a daywork basis. The design-as-you-go approach requires close supervision by an engineering geologist or rock engineer and the contractor should be experienced in stabilization work.

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